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RELIABILITY OF RUBBER CONVEYOR BELTS AS A PART OF THE OVERBURDEN REMOVAL SYSTEM − CASE STUDY: TAMNAVA-EAST FIELD OPEN CAST MINE

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Original scientific paper
This paper identifies the rubber belt conveyers' reliability function, operating on machines (bucket-wheel excavator, beltwagon, spreader) removing overburden on the Tamnava – East Field Open Cast Mine, depending on the belt length and operating time. The proposed methodology used to analyse operating time until failure is the basis to identify the reliability function. The methodology is based on the fact that belt operating time until failure may be represented by the composition of exponential distribution (sudden failures) and normal distribution (gradual failure), as well as on the fact that there is linear dependence between the belt length and the mean operating time until gradual failures. The proposed methodology and reliability function may be applied to analyse operation of other open cast mines, with certain adjustments, to provide better downtime planning, spare rubber belts planning, as well as to reduce open cast mine operating costs, i.e. optimal maintenance strategy.

Keywords: *failure time distribution, reliability function, rubber belt failure*

Pouzdanost gumenih traka trakastog transportera kao dijela sustava za otkopavanje jalovine − studija slučaja: površinski kop Tamnava istočno polje

Izvorni znanstveni članak
U radu je određena funkcija pouzdanosti gumenih traka na transporterima, koji rade na strojevima (rotorni bager, transporter, odlagač) pri otkopavanju jalovine na površinskom kopu "Tamnava Istočno polje", u ovisnosti o duljini trake i vremenu rada. Osnovu za određivanje funkcije pouzdanosti predstavlja predložena metodologija analize vremena rada do otkaza gumenih traka koja se temelji na činjenici da se vrijeme rada trake do otkaza može predstaviti kompozicijom eksponencijalne raspodjele (vrijeme rada do naglih otkaza) i normalne raspodjele (vrijeme rada do postepenih otkaza) kao i činjenici da postoji linearna ovisnost između duljine trake i srednjeg vremena rada do postepenih otkaza. Predložena metodologija kao i funkcija pouzdanosti mogu se, uz odgovarajuća prilagođavanja, primijeniti pri analizi rada drugih površinskih kopova radi kvalitetnijeg planiranja zastoja, potrebe za rezervnim gumenim trakama kao i za smanjenje troškova u radu površinskog kopa, tj. mogu ukazati na primjenu kvalitetnije (optimalne) strategije u održavanju.

Ključne riječi: *raspodjela vremena otkaza, funkcija pouzdanosti, otkaz gumene trake*

1 Introduction

Coal (lignite) mining in the Electric Power Industry of Serbia within the analysed period (1991 ÷ 2009) was carried out on six open cast mines in two basins: Kolubara and Kostolac. Continuous machinery was used to mine coal and remove overburden on all open cast mines. The Tamnava – East Field Open Cast Mine operation, located in the Kolubara Coal Basin, with the average coal production of some 7,5 million tons and overburden removal of some 10 million m^3bm (cubic metres of bulk material) was monitored to gather and analyse machinery operation data in terms of downtimes caused by the rubber belt failures on belt conveyers.

Overburden needs to be removed and dumped as a precondition for coal mining. The removed overburden is of heterogeneous composition and grain size, comprising gravel and several types of clay. Since 1979, overburden has been removed at the Tamnava – East Field Open Cast Mine by continuous machinery (ECS system) comprising a bucket-wheel excavator (theoretic capacity Q=4100 m^3bm/h [1]), beltwagon, spreader and a belt conveyer system. Steel core rubber belts (S_t=1600 N/cm), used for machine conveyers (bucket-wheel excavator, beltwagon, spreader) are 1600 mm wide. Sudden failures occur during belt conveyer operation when large pieces fall onto the belt, in addition to the usual wear. The transported material largely influences the reliability and operating time of rubber belts (with the same belt quality). Namely, it was established that belt wear is 4 to 5 times slower during coal than during overburden transport. [2]

For this reason, as well as due to the lack of data required to analyse the rubber belt failures during lignite transport within the investigated period, this paper will analyse only the rubber belt failures on belt conveyers transporting overburden.

The overburden excavation systems work round the clock, and maximum production can only be achieved through the maximum usage of equipment. However, poor design solutions and other unexpected problems limit their performance and effectiveness. Those problems, caused by inadequate reliability, maintainability characteristics and poor maintenance strategy, lead to unexpected breakdowns and failures which result in huge economic losses [3, 4].

This paper presents and verifies a methodology used to analyse operating time until rubber belt failure based on the fact that belt operation until sudden failures (belt tear, puncture, etc.) may be described by exponential distribution, while the belt operating time until gradual failures (wear) may be described by normal distribution. By applying the proposed methodology, we have analysed (statistically) the rubber conveyer belt failure data, for the period from 1991 to 2009, on the following machines: bucket-wheel excavator, beltwagon and spreader removing overburden.

The total of six rubber belts of different lengths on the above-indicated machines was analysed to identify the rubber belt reliability function depending on their length and operating time.

1.1 Literature review

Mining equipment complexity and size are continually increasing and therefore unplanned failures of mining equipment cause high repair (replacement) costs. On the other side, lost production costs are even more important. Those facts underline the importance of a reliability study of mining equipment [5].

Belt conveyor downtime is extremely expensive occasion in open cast mines which use continuous machinery. Therefore maintainability and reliability aspects of belt conveyors have to be taken into consideration in earliest phases of conveyor life cycle – design process. Due to this fact Moody suggests 5 aspects of the design function which should lead to higher degree of maintainability and reliability [6].

Also, poorly designed, selected or maintained auxiliary equipment, such as conveyor belt cleaners, loading points etc., can cause problems (stops) in conveyor work and shorten belt life time. Beside those problems, low reliability of auxiliary equipment affects efficiency of the whole excavation system which at the end leads to the reduced production of open cast mines. Tips how to design and select conveyor belt auxiliary equipment properly are given by Colijn [7], while experiences in utilization and maintenance of some auxiliary equipment on open cast mines are presented by Ignjatovic et al. [8].

Reliability research and failure analyses of belt conveyors are very important, due to the cost of technological processes in which belt conveyors are an integral element. According to [9], belt puncture resistance, slit resistance, fatigue testing of belts, investigation of belt splices are the basic experimental methods to assess reliability and the remaining rubber belt capabilities – resources. Bindzár et al. [10], propose several numerical methods to assess the remaining capabilities of rubber belts due to service quality.

Gathering and archiving data (experience) about existing belt conveyor systems (mining machines) work such as: belt lifetime, belt working time to failure, dismantling reasons, detrimental factors, conveyor failure causes, etc. have great importance in design process and play significant role in choosing proper maintenance strategy for similar belt conveyor systems. Gathered data can be also used for obtaining distributions of belt lifetime or working times to different failures, reliability functions of conveyor systems as well as for prediction of belt failures, conveyor downtimes, etc. [11].

Mendoza et al. [12] developed model, based on Artificial Neural Networks, to generate failure data for belts in order to predict reliability of conveyor systems with stochastic belt failures. Examples how lifetime data can be used for determining reliability function and distribution of lifetime are shown by Al-Hemyari [13] and Jiang et al. [14], respectively. Liu et al. [15], used the Weibull probability density functions to simulate reliability, optimize the design and reduce maintenance costs of the chain conveyor. Barabady and Kumar [5], performed reliability analysis on chrushing plants by using failure data in order to estimate the parameters of theoretical distributions which provide the best fit for failure pattern. Uzgoren and Elevli [16], showed that the times between successive failures for the mechanical systems of a dragline are not independent and identically distributed and use the nonhomogeneous Poisson process in order to predict the time to the next failure and thus determine the expected number of failures and reliability for different time periods.

Chookah et al. used superposition of the probability functions to compose degradations effects (phenomena: fatigue, corrosion) on oil pipelines. The probability functions superposition model unites various phenomena with the same effect. It may be applied to different categories of rubber belt failures and degradation [17].

A common conclusion of the above articles is a well-known fact - reliability increase can reduce maintenance costs. For rubber belts, it is significant to observe this fact in relation to belt length i.e. to find a mathematical dependence between reliability (i.e. maintenance costs), failure rates, belt length and operating time.

2 Downtime analysis methodology and ECS system time utilisation

From the reliability point of view, an ECS system may be considered as serial system, meaning that failure of any machine or sub-system causes the entire system to malfunction.

ECS system rubber belt failure data were taken over from the maintenance records of the Tamnava – East Field open cast mine. It should be noted that the analysed ECS system within the investigated period, 1991 ÷ 2009, removed overburden. Tab. 1 shows time utilisation coefficient – K_t of ECS system from year 1991 to 2009, calculated upon total calendar number of hours per year i.e. 8760. Six closed belts of different lengths have been considered. The following belt lengths were analysed: L_1=27,6 m, L_2=51,6 m, L_3=75 *m*, L_4=81,5 m, L_5=106,1 m and L_6=158,2 m.

The proposed methodology stems from the idea that rubber belt failure causes may be divided into two categories, which means that the distribution of operating time until failure caused by different failure categories is not the same.

Table 1 ECS system time utilisation coefficient – K_t

Year	K_t	Year	K_t	Year	K_t
1991	0,53	1998	0,38	2005	0,41
1992	0,47	1999	0,37	2006	0,59
1993	0,56	2000	0,32	2007	0,58
1994	0,53	2001	0,33	2008	0,61
1995	0,48	2002	0,31	2009	0,47
1996	0,54	2003	0,43		
1997	0,52	2004	0,43		

Depending on the nature of causes leading to failures, downtime data have been classified into two categories. The first category – gradual failures – includes downtimes caused by: belt wear, deterioration, replacement during annual maintenance, investment replacement, while the second category – sudden failures – includes downtimes caused by: joint damage, puncture, impact, belt tear.

In order to obtain the ‘effective operating time per year (h)’ for each analysed rubber belt (Tabs. 2 ÷ 7 and 10), the number of days in which rubber belt was functioning properly in a specific year, is multiplied with an adequate annual time utilisation coefficient K_t of overburden removal system (ECS system) [18].

2.1 Analysis of rubber belt operating time until gradual failures

Effective operating time of each belt according to years (obtained in the manner described above), the total operating time between failures (downtimes), as well as the mean operating time until gradual failures - $MTTF_{gf}^{L_i}$ (operating life), for each of the analysed belts, are shown in Tabs. 2, 3, 4, 5, 6 and 7.

Table 2 Operating time until gradual failures for belt L_1= 27,6 m

No.	Year	No. of days	Effective operating time per year / h	Total operating time / h
1	1992	37	417,36	
	1993	137	1841,28	2258,64
2	1994	242	3078,24	3078,24
3	1994	53	674,16	
	1995	116	1336,32	2010,48
4	1997	114	1422,72	1422,72
5	1998	122	1112,64	1112,64
6	2007	96	1336,32	
	2008	70	1024,80	2361,12
7	2008	88	1288,32	1288,32
8	2008	113	1654,32	1654,32
9	2008	95	1390,80	
	2009	260	2932,80	4323,60
			$MTTF_{gf}^{L1}$ / h	2167,79

Table 3 Operating time until gradual failures for belt L_2= 51,6 m

No.	Year	No. of days	Effective operating time per year / h	Total operating time / h
1	1992	135	1522,80	
	1993	117	1572,48	3095,28
2	1993	248	3333,12	
	1994	63	801,36	4134,48
3	1995	238	2741,76	
	1996	260	3369,60	6111,36
4	1996	51	660,96	660,96
5	1996	55	712,80	
	1997	200	2496,00	3208,80
6	1998	107	975,84	
	1999	57	506,16	1482,00
7	2008	254	3718,56	3718,56
8	2009	48	541,44	541,44
			$MTTF_{gf}^{L2}$ / h	2869,11

Table 4 Operating time until gradual failures for belt L_3= 75 m

No.	Year	No. of days	Effective operating time per year / h	Total operating time / h
1	1993	149	2002,56	
	1994	181	2302,32	4304,88
2	1995	101	1163,52	1163,52
3	1995	72	829,44	
	1996	366	4743,36	
	1997	295	3681,60	9254,40
4	1997	70	873,60	
	1998	301	2745,12	3618,72

Table 4 Operating time until gradual failures for belt L_3= 75 m (continued)

No.	Year	No. of days	Effective operating time per year / h	Total operating time / h
5	1999	143	1269,84	
	2000	366	2810,88	
	2001	365	2890,80	
	2002	189	1406,16	8377,68
6	2007	67	932,64	
	2008	299	4377,36	5310,00
7	2008	67	980,88	
	2009	261	2944,08	3924,96
			$MTTF_{gf}^{L3}$ / h	5136,31

Table 5 Operating time until gradual failures for belt L_4= 81,5 m

No.	Year	No. of days	Effective operating time per year / *h*	Total operating time / *h*
1	1991	155	1971,60	
	1992	366	4128,48	
	1993	293	3937,92	10038,00
2	1993	72	967,68	
	1994	273	3472,56	4440,24
3	1997	134	1672,32	
	1998	166	1513,92	3186,24
4	1998	197	1796,64	1796,64
5	1999	143	1269,84	
	2000	366	2810,88	
	2001	365	2890,80	
	2002	94	699,36	7670,88
6	2007	35	487,20	
	2008	276	4040,64	4527,84
7	2008	90	1317,60	
	2009	263	2966,64	4284,24
			$MTTF_{gf}^{L4}$ / h	**5134,87**

Table 6 Operating time until gradual failures for belt L_5= 106,1 *m*

No.	Year	No. of days	Effective operating time per year / h	Total operating time / h
1	1992	284	3203,52	
	1993	174	2338,56	5542,08
2	1994	285	3625,20	3625,20
3	1994	7	89,04	
	1995	95	1094,40	1183,44
4	1995	270	3110,40	
	1996	207	2682,72	5793,12
5	1996	159	2060,64	
	1997	240	2995,20	5055,84
6	1997	125	1560,00	
	1998	365	3328,80	
	1999	365	3241,20	
	2000	366	2810,88	
	2001	187	1481,04	12421,92
7	2008	94	1376,16	
	2009	259	2921,52	4297,68
			$MTTF_{gf}^{L5}$ / h	**5417,04**

Within the same period, shorter belts receive greater load and bend around the pulleys more than longer belts. In the case of gradual failures, this leads to faster wear and therefore to shorter (mean) operating time until failure, i.e. operating life, which is summarised in Tab. 8 on the basis of the above tables.

Table 7 Operating time until gradual failures for belt L_6= 158,2 m

No.	Year	No. of days	Effective operating time per year / h	Total operating time / h
1	1991	324	4121,28	
	1992	366	4128,48	
	1993	183	2459,52	10709,28
2	1993	182	2446,08	
	1994	211	2683,92	5130,00
3	1994	154	1958,88	
	1995	365	4204,80	
	1996	302	3913,92	10077,60
4	1997	6	74,88	
	1998	365	3328,80	
	1999	365	3241,20	
	2000	366	2810,88	
	2001	365	2890,80	
	2002	227	1688,88	14035,44
5	2003	288	2972,16	
	2004	366	3777,12	
	2005	365	3591,60	
	2006	365	5168,40	
	2007	89	1238,88	16748,16
6	2007	276	3841,92	
	2008	138	2020,32	5862,24
7	2008	228	3337,92	
	2009	258	2910,24	6248,16
			$MTTF_{gf}^{L6}$ / h	**9830,13**

Table 8 Mean belt operating time until failure depending on the belt length.

i	Belt length L_i / m	$MTTF_{gf}^{L_i}$ / h
1	27,6	2167,79
2	51,6	2869,11
3	75	5136,31
4	81,5	5134,87
5	106,1	5417,04
6	158,2	9830,13

Since the considered belts are of different lengths, to obtain a homogenous (representative) sample, the total operating time of shorter belts should be recalculated compared to the longest belt (L_6=158,2 m). To this end, we have established dependence between the mean operating time until failures and the belt length (Tab. 8).

The parameters of linear correlation and the correlation coefficient are determined using statistical software SPSS. [19]

The required linear correlation, shown in Fig. 1, has the following form:

$$MTTF_{gf} = 281{,}41+57{,}734 \cdot L. \quad (1)$$

Correlation coefficient, showing the correlation dependence strength, has the following value r = 0,976.

Since the correlation ratio value is close to one, the dependence between the mean operating time until gradual failure and belt length is absolute (strong). [20]

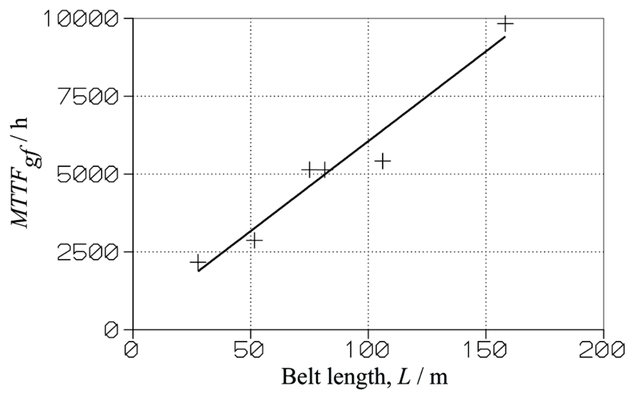

Figure 1 Dependence of the mean operating time until gradual failures from belt length

For the recalculation of the total operating time of shorter belts compared to the longest belt to make sense, it is necessary to verify the existence of statistic dependence between the belt length and operating time until gradual failures.

To verify the existence of statistic dependence between the belt length and operating time until failure, for the case of a small sample (n<30), Student's t-test is used. There is statistic dependence if [20]:

$$|t_0| > t_{\alpha/2,\,n-2},$$

where: $t_0 = r\sqrt{n-2}/\sqrt{1-r^2}$ = 9,02169 – decision statistics (r = 0,976 – correlation coefficient, n = 6), $t_{\alpha/2,\,n-2}$ – theoretic value of Student's t – distribution (for α = 0,05), i.e. $t_{\alpha/2,\,n-2} = t_{0{,}025;\,4} = 2{,}776$.

Since the calculation value of the decision statistics is higher than the theoretic value of the Student's t-distribution, it may be concluded that there is statistic dependence between belt length (L_i) and operating time until failure ($MTTF_{gf}^{L_i}$) caused by gradual failures, i.e. belt operating life expiry.

As pointed out above, to obtain a representative sample, operating time until failure of the following belts was adjusted (recalculated): L_1, L_2, L_3, L_4, L_5. Recalculation was done through the obtained linear dependence (1) compared to the longest belt L_6, by multiplying each of the operating times until failure for the given belt with the quotient of the mean operating times until failure of the longest belt and the given belt. Obtained results are shown in Tab. 9.

Sample shown in Tab. 9 was tested for affiliation to the truncated normal distribution of form: [21]

$$f(t) = \frac{c}{\sigma \cdot \sqrt{2\pi}} \cdot \exp\left[-\frac{(t-\bar{t})^2}{2 \cdot \sigma^2}\right], \quad (2)$$

where $\bar{t}$ – mean sample value, σ – mean square sample deviation, while coefficient c, for domain [0,+∞), is determined as: $c = 1/F_0(\bar{t}/\sigma)$, where $F_0(x)$ – function of the standard normal distribution of argument x.

Affiliation of the sample obtained in the above manner to the theoretic distribution (2) was established by applying χ^2 - test. Specially designed software [22] was used for applying χ^2 – test due to uncommon shape of normal distribution – truncated normal distribution.

Testing result obtained by applying the χ^2 – test indicated that the sample shown in Tab. 9 could be described with the truncated normal distribution characterised by parameters $\bar{t}$ = 9556,69, σ = 4967,05 and c = 1,0279389 with the relevance threshold of α = 0,01 (Fig. 2).

Table 9 Recalculated belt operating times until gradual failures.

L_i		TTF / h	L_i		TTF / h	L_i		TTF / h	L_i		TTF / h	L_i		TTF / h	L_i		TTF / h
L_1 = 27,6 m	1	11342,09	L_2 = 51,6 m	1	8937,88	L_3 = 75 m	1	8789,00	L_4 = 81,5 m	1	18951,70	L_5 = 106,1 m	1	8143,97	L_6 = 158,6 m	1	10709,28
	2	15457,82		2	11938,66		2	2375,49		2	8383,15		2	5327,15		2	5130,00
	3	10095,91		3	17647,07		3	18894,12		3	6015,61		3	1739,04		3	10077,60
	4	7144,39		4	1908,58		4	7388,11		4	3392,05		4	8512,86		4	14035,44
	5	5587,28		5	9265,68		5	17104,18		5	14482,59		5	7429,45		5	16748,16
	6	11856,70		6	4279,40		6	10841,09		6	8548,54		6	18253,74		6	5862,24
	7	6469,48		7	10737,66		7	8013,34		7	8088,63		7	6315,35		7	6248,16
	8	8307,41		8	1563,45												
	9	21711,58															

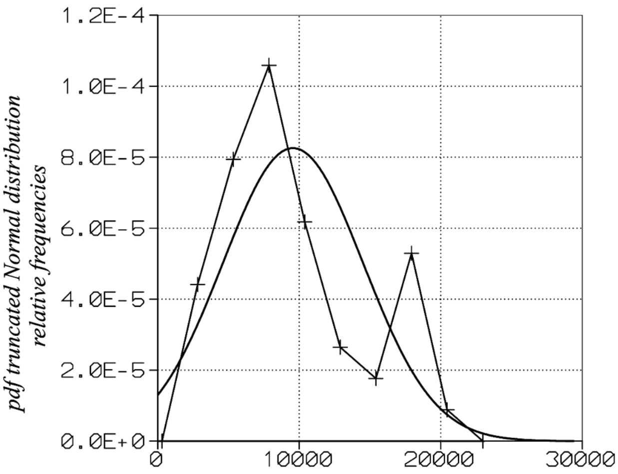

Figure 2 Operating time until failure distribution in the case of gradual failures.

Finally, results shown in Fig. 2 mean that rubber belt operating time until failure, caused by gradual failures i.e. belt operating life, can be described with truncated normal distribution.

2.2 Analysis of rubber belt operating time until sudden failures

In the second category – sudden failures (puncture, impact, tear and other damages) are usually caused by the load falling onto the belt. They may occur at any given moment, regardless of whether the belt is new or regenerated, i.e. long or short. Due to such downtime nature, there is no dependence between the belt operating time and the belt length (L), hence, there is no need to recalculate time.

In the case of downtimes from the sudden failures category, 'effective operating time (h)' of belts according to years is obtained, as in the above case, when the number of calendar days in which the ECS system was in operation in the given year is multiplied with an adequate annual time utilisation coefficient – K_t. (Tab. 1).

Effective operating time for each belt according to years is shown in Tab. 10, while the 'Total operating time (h)' column represents a sample to be tested for affiliation to the exponential distribution. The last column of Tab. 10 contains mean operating time until failure in the case of sudden failures for each of the considered belts $MTTF_{sf}^{L_i}$.

Table 10 Rubber belt operating time until sudden failures

L_i / m	No.	Year	No. of days	Effective operating time per year / h	Total operating time / h	$MTTF_{sf}^{L_i}$ / h
L_1 = 27,6 m	1	1993	122	1639,68	1639,68	
	2	1993	106	1424,64		
		1994	70	890,40	2315,04	
	3	1995	83	956,16	956,16	
	4	1997	168	2096,64		
		1998	103	939,36	3036,00	
	5	1998	51	465,12	465,12	
	6	1998	37	337,44	337,44	
	7	1998	52	474,24		
		1999	87	772,56	1246,80	
	8	1999	32	284,16	284,16	
	9	1999	94	834,72	834,72	
	10	1999	145	1287,60	1287,60	
	11	1999	7	62,16		
		2000	366	2810,88		
		2001	365	2890,80		
		2002	365	2715,60		
		2003	21	216,72	8696,16	**1918,08**
L_2 = 51,6 m	1	1994	302	3841,44		
		1995	127	1463,04	5304,48	
	2	1997	165	2059,20		
		1998	211	1924,32	3983,52	
	3	1998	47	428,64	428,64	
	4	2008	96	1405,44		
		2009	146	1646,88	3052,32	**3192,24**
L_3 = 75 m	1	1992	216	2436,48		
		1993	121	1626,24	4062,72	
	2	1993	95	1276,80	1276,80	
	3	1994	184	2340,48		
		1995	192	2211,84	4552,32	
	4	1998	64	583,68		
		1999	222	1971,36	2555,04	
	5	2002	176	1309,44		
		2003	59	608,88	1918,32	
	6	2003	41	423,12	423,12	
	7	2003	23	237,36	237,36	
	8	2003	3	30,96	30,96	**1913,04**

Table 10 Rubber belt operating time until sudden failures (continued)

L_i / m	No.	Year	No. of days	Effective operating time per year / h	Total operating time / h	$MTTF_{sf}^{L_i}$ / h
$L_4 = 81,5$ m	1	1998	2	18,24		
		1999	222	1971,36	1989,60	
	2	2002	271	2016,24		
		2003	212	2187,84	4204,08	
	3	2009	102	1150,56		
		2010	95	524,40	1674,96	**2622,88**
$L_5 = 106,1$ m	1	1993	191	2567,04		
		1994	19	241,68	2808,72	
	2	1994	54	686,88	686,88	
	3	2001	178	1409,76		
		2002	365	2715,60		
		2003	250	2580,00	6705,36	
	4	2007	97	1350,24		
		2008	272	3982,08	5332,32	**3883,32**
$L_6 = 158,2$ m	1	1996	64	829,44		
		1997	132	1647,36	2476,80	
	2	1997	227	2832,96	2832,96	
	3	2002	138	1026,72		
		2003	77	794,64	1821,36	**2337,04**

The sample shown in Tab. 10 (column 6) was tested for affiliation to the exponential distribution:

$$f(t) = \lambda \cdot \exp\left[-\lambda \cdot t\right], \tag{3}$$

where λ – exponential distribution parameter.

Test result obtained by applying the χ^2 – test [22] indicates that the sample shown in Tab. 10 could be described by the exponential distribution with the parameter λ = 0,0005 and the relevance threshold of α = 0,01 (Fig. 3).

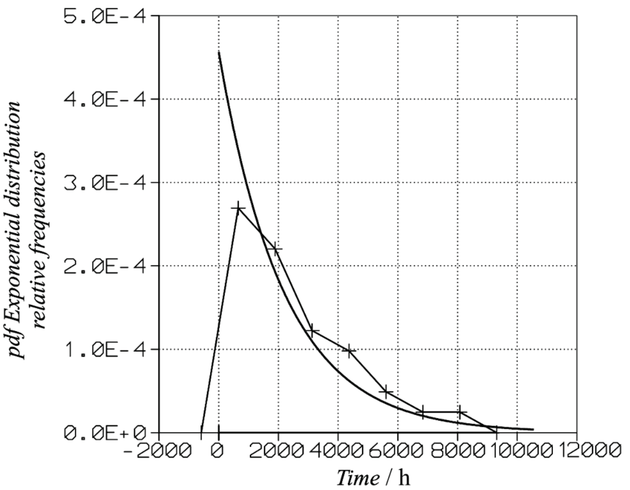

Figure 3 Operating time until failure distribution in the case of sudden failures

Results, shown in Fig. 3 mean that rubber belt operating time until failure, caused by sudden failures is exponentially distributed.

3 Rubber conveyer belt reliability function

As indicated above, rubber belt failures causing belt conveyers i.e. overburden removal system to malfunction may be divided in two categories: sudden failures (exponentially distributed operating times until failures) and gradual failures (operating times until failures according to the truncated normal distribution). In both cases, it is assumed that failures are instantaneous while failure clear up is done by belt replacement. In the case of gradual failures belt replacement can be planned in advance which cannot be done in the case of sudden failures.

Superposition of the above two distributions corresponds to the case occurring in reality, i.e. when both sudden and gradual failures can occur during belt operation.

Superposition density of these two distributions is as follows [21]:

$$f(t) = c_1 \cdot \lambda \cdot \exp\left[-\lambda \cdot t\right] + c_2 \cdot \frac{\mathrm{c}}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot \exp\left[-\frac{(t-\bar{t})^2}{2 \cdot \sigma^2}\right], \tag{4}$$

where ratios c_1 and c_2 are determined from the relation of sudden and gradual failures frequency.

The sample tested for affiliation to the superposition of the exponential and the truncated normal distribution is obtained by integrating the sample belonging to the sudden failure category (Tab. 10) and the sample belonging to the gradual failures category (Tab. 9). Ratios c_1 and c_2 are determined as the relation between the number of sample members from the individual sample (sudden failure or gradual failure) and the number of members of the integrated sample.

Test results obtained by applying the χ^2 – test, using designed software [22] due to complex form of expression (4), indicated that the integrated sample could be described by a distribution representing the superposition of the exponential and the truncated normal distribution with parameters λ = 0,0005, $\bar{t}$ = 9556,69, σ = 4967,05 and c = 1,0279389 and the relevance threshold of α = 0,01 (Fig. 4).

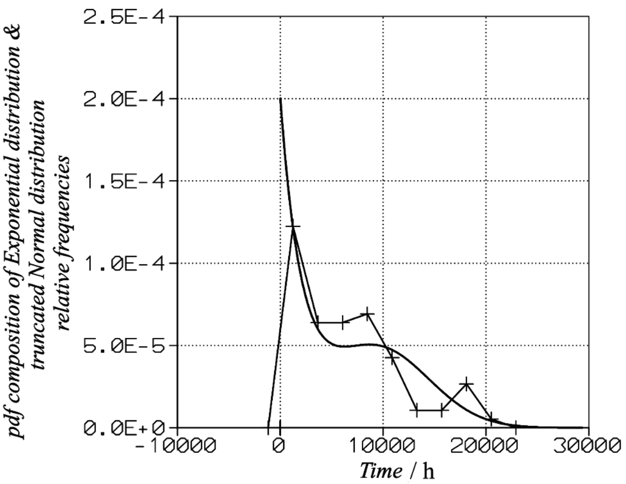

Figure 4 Distribution of operating time until failures in the case of sudden and gradual failures

Distribution of rubber belt operating time until failure (sudden or gradual), shown in Fig. 4, can be obtained as superposition of exponential (sudden failures) and truncated normal distribution (gradual failures).

Belt unreliability function $F(t)$ is obtained by integrating the superposition density of the exponential and truncated normal distributions (4), i.e. [21]:

$$F(t)=\int_0^t \left(c_1\cdot\lambda\cdot\exp\left[-\lambda\cdot t\right]+ +c_2\cdot\frac{\mathrm{c}}{\sigma\cdot\sqrt{2\cdot\pi}}\cdot\exp\left[-\frac{(t-\bar{t})^2}{2\cdot\sigma^2}\right]\right)\cdot \mathrm{d}t. \quad (5)$$

Unreliability function may be written in the following form:

$$F(t)=c_1\cdot(1-\exp\left[-\lambda\cdot t\right])+c_2\cdot\frac{c}{2}\cdot\mathrm{erf}\left[\frac{t-\bar{t}}{\sigma\cdot\sqrt{2}}\right]+K,$$

where: $K=c_2\cdot\frac{c}{2}\cdot\mathrm{erf}\left[\frac{\bar{t}}{\sigma\cdot\sqrt{2}}\right]$, (6)

while $\mathrm{erf}\,(x)=\frac{2}{\sqrt{\pi}}\cdot\int_0^x \mathrm{e}^{-t^2}\cdot\mathrm{d}t$ is the error function.

Approximate formula is used to calculate the error function, e.g. [23]:

$$\mathrm{erf}\,(x)=1-(a_1\cdot z+a_2\cdot z^2+a_3\cdot z^3)\cdot\mathrm{e}^{-x^2},$$

where:

$z\equiv\frac{1}{1+p\cdot x}$, while the constants have the following values:

$p=0{,}47047$; $a_1=0{,}3480242$;

$a_2=-0{,}0958798$; $a_3=0{,}7478556$.

By replacing the expression (1) representing the dependence of the mean operating time until gradual failures from the belt length L, in expression (6) and by subtracting it from one, the following expression for the rubber belt reliability function depending on time and belt length, i.e. $R(t,L)$ is obtained:

$$R(t,L)=1-F(t,L). \quad (7)$$

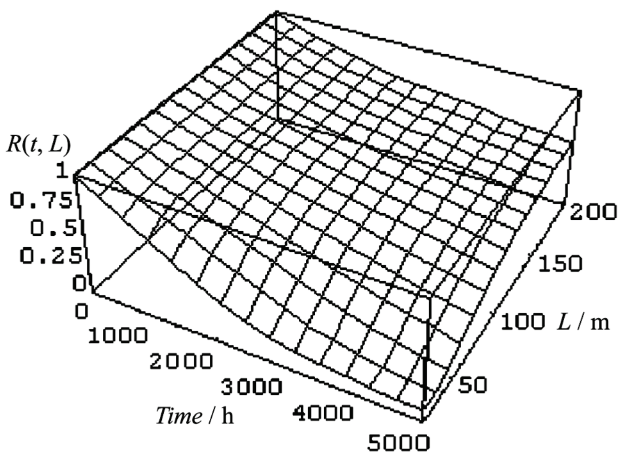

Figure 5 Rubber belt reliability function change, $R(t,L)$

The change of reliability function $R(t,L)$, depending on the belt length L and time, given in Fig. 5, shows that longer rubber belts are more reliable than shorter ones for the same operating time. In other words, it has been proven that reliability decreases in the case of shorter rubber belts. This can be explained with the fact that shorter rubber belts reach a bigger number of bending around pulley. Namely, it is well-known that the increased number of stress state changes cause shorter life time of the operating element, i.e. in this case shorter rubber belts are more prone to fatigue and wear.

4 Conclusion

For large mining systems like overburden removal systems, it is important to determine when the equipment in a system will break down, or how long it will perform in a reliable manner in order to take the necessary precautions to ensure continuity of the system operation due to huge lost production costs. Therefore the proposed methodology is designed to assist persons in charge in planning and adopting adequate maintenance strategies, planning of conveyor maintenance expenses and optimization of inventory policy.

The following conclusions were reached by analyzing and processing data found in the machinery maintenance records of the Tamnava – East Field Open Cast Mine and by applying the proposed methodology.

Operating time until failure of rubber conveyer belts, operating on machines such as: bucket-wheel excavator, beltwagon and spreader, may be described on the basis of the two following distributions: exponential and truncated normal. In other words, belt operating time until failure behaves according to a complex mathematic model, where the operating time until sudden failures (tear, puncture, etc.) is described by exponential distribution, while the operating time until gradual failures caused by regular wear is described by truncated normal distribution. Analysis of rubber belt operating time until failure as a complex phenomenon provides a higher quality downtime planning, spare rubber belts planning as well as open cast mine operating costs reduction.

It was established that there is linear dependence between the mean belt operating time and its length, in the case of gradual failures. The above dependence together with the distribution composition describing belt operating time until failure was used to determine belt reliability function depending on belt length and operating time. The obtained dependence confirms a fact that longer belts are in general more reliable than shorter ones.

Presented results are obtained by applying the proposed rubber belts failure analysis methodology to operating conditions of the Tamnava – East Field open cast mines, while the proposed methodology may be applied, with certain adjustments, to other open cast mines to indicate that a higher quality (optimal) maintenance strategy may reduce rubber belt failures.

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